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MULTI-PHYSICS ANALYSIS OF CW SUPERCONDUCTING CAVITY FOR THE LCLS-II USING ACE3P*

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Abstract

The LCLS-II linac utilizes superconducting technology operating at continuous wave to accelerate the 1-MHz electron beams to 4 GeV to produce tunable FELs. The TESLA 9-cell superconducting cavity is adopted as the baseline design for the linac. The design gradient is approximately 16 MV/m. The highest operating current is 300 µA. Assuming that the RF power is matched at the highest current, the optimal loaded Q_L of the cavity is found to be around 4×10^7. Because of the high Q_L, the cavity bandwidth approaches the background microphonic detuning, and the performance of the cavity is tightly coupled to the mechanical perturbations of the cavity/cryomodule system. The resulting large phase and amplitude variations in the cavity require active feedback to achieve the 0.01% amplitude and phase stability requirements. To understand the cavity RF response and feedback requirements to the microphonics and Lorentz Force detuning, we have developed a simulation model of the RF-mechanical coupled system using parameters obtained with the multi-physics solver ACE3P. We will present the simulation results of the preliminary study of the mechanical resonance of the LCLS-II RF cavity and the reduced model to be used in the analysis of RF station topologies and feedback schemes.

INTRODUCTION

LCLS-II [1,2] will use a CW SRF linac to deliver high-brightness and high-repetition-rate electron beams for the FELs. The machine is design for 1-MHz reprate with a max current of 300 µA. The nominal beam energy is 4 GeV. The linac will be based on the TESLA 9-cell cavity design [3] with an unloaded Q_0 of 2.7×10^{10} and a Qext of 4×10^7. The nominal gradient is 16 MV/m. Lorentz Force Detuning (LFD) remains important in CW operation for RF turn-on, and trips caused on/off cycles. The frequency sensitivity to pressure variations, df/dP, is important to minimize the coupling between the RF to the Helium pressure fluctuations. An end-lever tuner is proposed for the LCLS-II cavities. The frequency sensitivity to pressure variations and LFD depends on the design of the stiffening of the cavity and end-plates as well as the tuner strength, which can be optimized. To be able to operate the CW machine reliably, the resonance frequency change due to mechanical vibrations caused by external vibration sources and LFD need to be compensated. A simulation model for the RF-mechanical coupled system is being developed to understand the cavity RF response and feedback requirements to the microphonics and LFD. The parameters of this model were obtained using the parallel multi-physics (RF, thermal, mechanical) solvers of ACE3P [4,5].

The cavity models being studied are shown in Fig. 1. The model for the mechanical analysis includes the 2.8-mm thick cavity shell, the stiffness rings, Helium vessel and bellows, and a simplified tuner. The properties of the materials used in the simulation are shown in Table 1. The domain for the RF analysis is the inside vacuum volume of the cavity. The bound surface of the vacuum volume is the interface surface for mapping the RF solutions to the mechanical solver and vise versa. In this paper, we present the preliminary results of the ongoing study of the mechanical resonance of the LCLS-II SRF cavity and the reduced model to be used in the analysis of RF station topologies and feedback schemes.

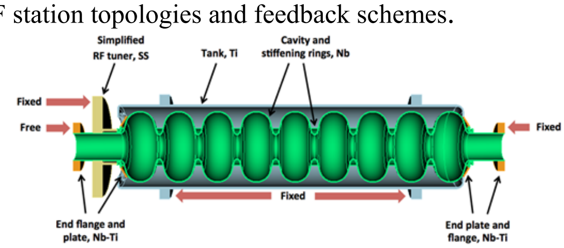

Figure 1: LCLS 9-cell cavity with Helium tank.

Table 1: Material Properties

Properties	Nb	Nb-Ti	Ti	SS
Density, ρ [kg/m^3]	8700	5700	4540	8000
Poisson Ratio, υ	0.38	0.33	0.37	0.29
Lowest acc HOM	118	68	117	193

LORENTZ FORCE DETUNING AND DF/DP

The Helium vessel is welded to the cavity end-plate on one end and is connected to the cavity by a bellows on the other end so it does not assert significant resistance to the frequency tuner. The beam pipe flange on the welded side of the Helium vessel is fixed in position while the flange on the other end is connected to the beam pipe which has a bellows. These set of bellows allow one side of the cavity to move “freely” to accommodate the geometry change during the cool down and warm up and the frequency tuning by the tuner. These bellows contribute relatively weak constraints to the cavity length change. The frequency tuner on the other hand holds the cavity tight to maintain the cavity frequency. The cavity length change due the Lorentz force and Helium pressure and etc work against the tuner and could elastically deform it so the tuner asserts an elastic constraint to such cavity geometry changes. The effect of the tuner elastic strength on the LFD and dF/dP is evaluated for different

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stiffness ring radii. In the simulation model, the tuner is simplified to a pair of stainless steel rods of equivalent spring constant (K=YA/L, Y=Young's Modulus, A=area, L=length).

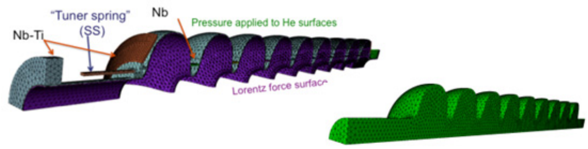

Figure 2: The mesh and material type of the mechanical model (top) and the vacuum mesh for RF calculation.

Lorentz Force Detuning (LFD)

The LFD is the frequency change due to the cavity shape deformation by the electromagnetic pressure on the cavity surface. The LFD coefficient was calculated in three simulation steps: calculate the RF modes on the vacuum mesh, Fig. 2 right, using the RF eigenmode solver, calculate the cavity shape deformation on the mechanical mesh, Fig. 2 left, under the RF pressure, $P=(\mu_0 H^2-\varepsilon_0 E^2)/4$, using the mechanical analysis solver, then map the deformed mechanical cavity shape onto the vacuum mesh and calculate the RF frequency change due to the deformation. The LFD coefficient is then calculated as $K_l = \Delta F / E^2_{acc}$. Figure 3 shows the electric and magnetic fields that assert Lorentz force pressure to the inner surface of the cavity shell. Figure 4 shows the geometries of the cavity with and without Lorentz force deformation. One notice that the cavity end-plate on the tuner end (left) is twisted due to the Lorentz force that works against the tuner retention force. A more rigid end-pate may reduce the K_L. The dependence of LFD on tuner strength and stiffness ring radius is shown in Fig. 5.

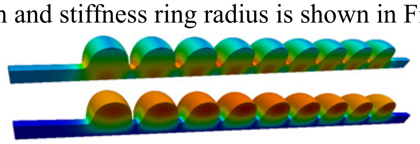

Figure 3. Electric and magnetic field on the cavity wall that generate RF pressure.

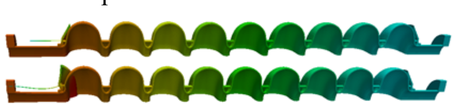

Figure 4: Cavity shape with (bottom) and without (top) Lorentz force.

dF/dP

The frequency change due to the Helium pressure is calculated using the mechanical analysis solver. The Helium pressure is applied to the inner side of the end-

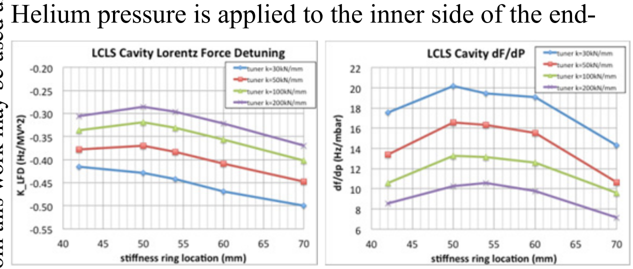

Figure 5: Lorentz force detuning (left) and dF/dP versus stiffness ring position.

plates and the cavity outer shell surfaces. The outer tank was not included in this model as the geometry change of the outer tank has a little effect to the cavity body because of the bellows. However these details will be included in the future analysis. Figure 6 shows a deformed cavity body under the Helium pressure and tuner elastic constraint. The dependence of dF/dP on the tuner strength of the stiffness ring position is shown in Fig. 6.

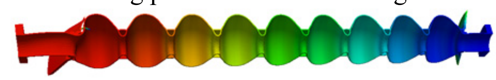

Figure 6: Cavity deformation due to helium pressure.

The stiffness ring radius has opposite effects on the dF/dP and LFD. A larger stiffness ring radius reduces the dF/dP while increases the LFD. The LFD is minimal at a stiffness ring radius of around 50 mm while the dF/dP is close to its maximum. A stiffener tuner can effectively minimize both sensitivities.

MECHANICAL MODES

The geometry used for the mechanical mode calculation is as shown in Fig. 1. The rod representation of the tuner used in the LFD and dF/dP calculations won't be suitable as both the normal and sheer elasticity strengths need to be included for the longitudinal and transverse mechanical modes. In this preliminary study, we used a cylindrical disk to model the tuner. We plan in the future to include more details of the tuner geometry that can represent the elastic properties. Mechanical modes were calculated for cavity with different stiffness ring radii. The table in Fig. 7 listed the first 21 mechanical modes. The mode in blue text are the longitudinal modes and the other modes are either cavity transverse modes or the modes of the Helium vessel. It worthwhile to mention that each transverse mode frequency listed in Table 1 represents a pair of orthogonal modes in x and y planes due to symmetry. The pictures in Fig. 7 are the mechanical mode patterns.

Stiffness ring radius (mm), frequency (Hz)				
42	50	54	60	70
56.8	67.8	74.1	84.9	105.5
127.1	148.6	160.9	181.7	216.5
182.5	204.8	219.9	248.2	302.5
233.6	259.9	265.0	274.3	305.8
252.8	279.0	306.0	358.5	483.1
346.7	407.1	437.3	493.9	583.4
362.3	409.6	450.7	530.0	607.0
432.7	516.5	559.1	583.5	623.8
511.8	580.9	605.0	625.4	754.0
536.9	604.7	625.2	714.5	758.2
553.1	625.3	650.0	734.8	912.8
582.4	633.2	709.6	754.5	978.2
601.2	704.1	754.5	872.6	1020.9
625.7	747.6	801.5	968.2	1134.4
703.2	754.4	854.9	978.6	1171.2
754.6	794.5	860.3	1002.5	1216.0
856.9	972.9	978.5	1089.3	1257.5
978.8	978.7	1048.5	1135.5	1280.9
991.7	1134.4	1135.4	1170.3	1297.3
1095.9	1135.3	1168.8	1190.5	1430.3
1135.6	1168.3	1225.4	1257.6	1497.9

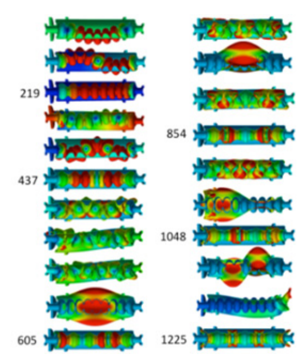

Figure 7: Mechanical modes.

The mechanical frequency increases as the stiffness ring radius increased. Mechanical modes excited by external sources (and LFD during rise time) cause an RF frequency detuning and thus a reduction of the RF field, which in turn cause additional RF frequency shift due to the LFD. A model for the control and feedback analysis is being developed to study the effects of mechanical modes and the stability of cavity operation.

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REDUCED CAVITY MODEL

In this section, we present a reduced cavity model to be used to simulate the RF-mechanical coupled system. Following [6], a mechanical displacement in the cavity structure can be decomposed in a complete infinite set of orthonormal mechanical modes. The amplitude of each mechanical mode can be represented by

$$\ddot{q}_u + \frac{2}{\tau_u}\dot{q}_u + \Omega_u^2 q_u = \frac{\Omega_u^2}{c_u} F_u$$

where q_u is the amplitude, F_u the mechanical force, c_u the elastic constant, Ω_u the frequency and τ_u the decay time of mechanical mode u. The frequency shift $\delta\omega_u$ caused by the mechanical mode u is proportional to q_u, and the force F_u due to radiation pressure which is proportional to the square of the field amplitude. The equation for $\delta\omega_u$ is

$$\delta\ddot{\omega}_u + \frac{2}{\tau_u}\delta\dot{\omega}_u + \Omega_u^2 \delta\omega_u = -k_u \Omega_u^2 v_c^2(t) \quad (1)$$

where k_u represents the coupling between the RF and the mechanical mode u. This equation describes how the cavity frequency is affected by the field amplitude.

On the other hand, the field amplitude depends on the frequency detuning between the cavity and the RF source. This relationship can be analyzed by solving the differential equation representing the field in the cavity, assuming it is driven by a generator where the amplitude and phase of this signal are considered as independent variables. Using in-phase/quadrature formalism to represent the resulting differential equation,

$$\begin{bmatrix} \dot{v}_{cIN}(t) \\ \dot{v}_{cQ}(t) \end{bmatrix} = \begin{bmatrix} -\omega_{BW} & -\Delta\omega(t) \\ \Delta\omega(t) & -\omega_{BW} \end{bmatrix} \begin{bmatrix} v_{cIN}(t) \\ v_{cQ}(t) \end{bmatrix} + R\omega_{BW} \begin{bmatrix} i_{kIN}(t)+i_{bIN}(t) \\ i_{kQ}(t)+i_{bQ}(t) \end{bmatrix} \quad (2)$$

where $v_{cIN}(t)$, $v_{cQ}(t)$ are the in-phase /quadrature voltages of the cavity, i_k and i_b are the driving current and beam current, respectively and $\Delta\omega(t) = -\omega_{RF} + \omega_{oN} + \delta\omega(t)$. It is important to observe in eqns. (1) and (2), there are two coupling terms between the field amplitude and the detuning. The mechanical modes are forced by the EM fields through the term $-k_u\Omega_u^2 v_c^2(t)$ and the field is affected by the cavity detuning by $\Delta\omega(t)\left[v_{cIN}(t) \;\; v_{cQ}(t)\right]^T$.

This reduced model allows analyzing the stability and performance of the RF station for different topologies, e.g. single cavity, multiple cavities, etc. and different operation conditions in closed loop. From the multiple configurations, let us pick the simplest case that is when the cavity is driven by a generator in open loop. The reduced model is $\dot{x} = f(x) + g(x)u$, with $x = \left[v_{cIN}(t) \;\; v_{cQ}(t) \;\; \delta\dot{\omega}_1 \;\; \delta\omega_1 \ldots \delta\dot{\omega}_u \;\; \delta\omega_u \ldots\right]^T$, then $\dot{x} = 0 = f(x_0) + g(x_0)u$ defines the operation point. Linearizing $\dot{x} = f(x) + g(x)u$ around the operation point one obtains $\delta\dot{x} = A\delta x + Bu$, with $\delta x = x - x_0$.

The eigenvalues of A define the stability of the operation point. It is possible to analyze the stability for changes in multiple parameters. Let us analyze the case of the LCLS-II cavity where the field is set at 16MV/m and the detuning ω_{oN} is changed and used as parameter to analyze the stability of the system in different conditions.

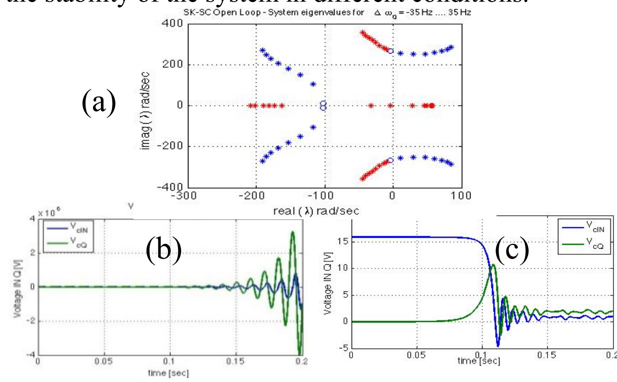

Figure 8: System eigenvalue and time domain simulation.

Figure 8 (a) shows the system eigenvalues assuming one mechanical mode for detuning Δω = -35Hz, -10Hz, 5Hz, 0Hz, 2.5Hz, 5Hz, 15Hz, 35Hz. The mechanical modes become unstable, for Δω < -0.88Hz. The RF eigenvalues are unstable if Δω >5.5Hz. Figure 8 (b) shows the v_{cIN}, v_{cQ} voltages when the mechanical mode is unstable and Fig. 8 (c) shows the v_{cIN}, v_{cQ} voltages when the EM mode is unstable.

SUMMARY

The multiphysics solver ACE3P was used to calculate the dF/dP, Lorentz Force detuning and mechanical eigenmodes of the LCLS-II cavity. The impact of stiffness ring radius and the tuner elastic strength on the dF/dP and Lorentz Force detuning was compared. Changing the stiffness ring radius has opposite effects on the dF/dP and LFD. The tuner stiffness can effectively minimize both sensitivities. The mechanical mode frequencies also increases as the stiffness ring moved outward. The coupling of these modes to the RF are being calculated. A reduced cavity model is being developed to analyze the coupled RF-mechanical system. Parameters for coupled system will be extracted from the results of the ACE3P multiphysics solvers.

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